E9158
12-14-94

NASA Technical Memorandum 106746

A Review of Transmission Diagnostics Research at NASA Lewis Research Center

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December 1994

National Aeronautics and
Space Administration

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SUMMARY

This paper presents a summary of the transmission diagnostics research work conducted at NASA Lewis Research Center over the last four years. In 1990, the Transmission Health and Usage Monitoring Research Team at NASA Lewis conducted a survey to determine the critical needs of the diagnostics community. Survey results indicated that experimental verification of gear and bearing fault detection methods, improved fault detection in planetary systems, and damage magnitude assessment and prognostics research were all critical to a highly reliable health and usage monitoring system. In response to this, a variety of transmission fault detection methods were applied to experimentally obtained fatigue data. Failure modes of the fatigue data include a variety of gear pitting failures, tooth wear, tooth fracture, and bearing spalling failures. Overall results indicate that, of the gear fault detection techniques, no one method can successfully detect all possible failure modes. The more successful methods need to be integrated into a single more reliable detection technique. A recently developed method, NA4*, in addition to being one of the more successful gear fault detection methods, was also found to exhibit damage magnitude estimation capabilities.

INTRODUCTION

Transmission diagnostics is becoming an increasingly important area of research within the rotorcraft community as transmission fault related accidents and fleet groundings continue to plague helicopters at an increasing rate. An investigation of serious rotorcraft accidents that were a result of fatigue failures showed that 32 percent were due to engine and transmission components (ref. 1). In addition, governmental aviation authorities are demanding that, in the near future, the safety record of civil helicopters must match that of conventional fixed-wing turbojet aircraft. Practically, this can only be accomplished with the aid of a highly reliable, on-line Health and Usage Monitoring (HUM) system. Although a variety of organizations are working in this area, only a few are working on the development and experimental verification of the basic elements of a HUM system. As a result, a HUM research team was formed to address current and future technology barriers in transmission diagnostics, utilizing the unique experimental facilities at NASA Lewis Research Center.

In 1990, the HUM research team conducted a survey to determine the critical needs of the diagnostics community. Participants of the survey included key personnel in U.S. industry and government agencies who work in or have direct influence on transmission diagnostics. In the survey the participants were asked to rate the need of a number of proposed research areas. Each of the research areas were rated individually as either critically needed, moderately needed, or not needed in the overall effort of developing a highly reliable HUM system. Results of the survey are presented in table I. As seen in the table, verification of current, state-of-the-art gear and bearing diagnostic methods and damage level assessment were deemed critical to the development of a highly reliable HUM system by a large majority of participants. A majority of the participants also considered prognostics and improving fault detection in planetary systems to be critical HUM research areas. To address these key areas, the HUM team initiated a

number of research projects that use the gear fatigue test rigs at NASA Lewis for experimental verification.

Several projects involved applying a number of state-of-the-art and newly developed gear fault detection techniques to experimental data from a spur gear fatigue rig, spiral bevel gear fatigue rig, and a face gear fatigue rig to verify and compare their relative performance. FM0, a coarse fault detection parameter, and FM4, an isolated fault detection parameter are the most widely referenced time domain discriminant methods for gear fault detection (ref. 11). M6A and M8A are variations of FM4, where the sixth and eighth statistical moments of the time signal are used to detect surface damage (ref. 9). The instantaneous phase of the demodulated time signal is used to detect gear tooth cracks and spalls (ref. 10). The instantaneous frequency of the demodulated time signal is also used as a method to detect gear tooth surface damage (refs. 7 and 8). NA4* and NB4* are methods recently developed at NASA Lewis to provide early detection of gear tooth surface damage and to continue to react to the damage as it spreads and grows in severity (ref.13).

Another project focused on improving planet gear fault detection in an epicyclic system. Standard time synchronous averaging techniques cannot be applied to planet gears in an epicyclic system. To improve gear fault detection in a planetary system, an enhancement technique was developed to obtain the individual vibration signal for each planet in the system (ref. 5).

Several other projects involved applying more general fault detection techniques to experimental data, using the test rigs at NASA Lewis. A new pattern classification technique (ref. 2) was applied to experimental data from NASA's 500 Hp helicopter transmission test rig in which a variety of gear and bearing failures were recorded. This method is similar to a neural network. However, unlike a neural network, it requires only a minimum amount of training. General failure detection using an on-line oil debris monitoring device was also evaluated using the experimental data from the 500 Hp transmission test rig (ref. 6). A joint time-frequency domain method, based on the Wigner-Ville Distribution, was recently developed to detect gear and bearing failures in a gear transmission system (ref. 3). This new joint time-frequency domain method was applied to spiral bevel gear fatigue data to determine the applicability of this method in predicting gear faults.

The ultimate objective of all of the research work described above is to enable the development of a highly reliable HUM system. Experimental verification of the fault detection methods, and improvements in the ability to detect gear and bearing faults in a transmission system are crucial steps in the overall process of developing a highly reliable HUM system.

This paper reviews each fault detection method and device evaluated, and summarizes their results and relative performance when applied to experimental data. Based on individual and comparison results, some general conclusions are presented.

TEST APPARATUS AND SAMPLE RESULTS

All of the experimental data used to verify the various fault detection methods was obtained using a number of test rigs operating at NASA Lewis Research Center. These rigs are: the spur gear fatigue rig, the spiral bevel gear fatigue rig, the face gear fatigue rig, and the 500 Hp transmission test rig. The primary purpose of these rigs is not for diagnostic studies, however, due to the nature of the tests being conducted on them, these rigs have become a valuable source of data for transmission diagnostics research. A short description of each rig, along with an example of the resulting experimental data obtained on each rig is given in the following paragraphs.

A graphical sketch of the spur gear fatigue rig at NASA Lewis is shown in figure 1. The primary purpose of this rig is to study the effects of gear materials, gear surface treatments, and lubrication types on the surface fatigue strength of aircraft quality gears. The test gears are run offset to maximize contact stress, while minimizing bending stress. Vibration data from an accelerometer mounted on a bearing end plate was captured on a personal computer with an analog to digital conversion board. The test gears are

standard spur gears having 28 teeth and a pitch diameter of 88.9 mm (3.50 in.). The gears were loaded to 74.6 Nm (660 in./lb) at an operating speed of 10 000 rpm. Figure 2 shows a sample of the heavy pitting damage found on a gear tooth surface at the end of a test on the spur gear rig. A total of five tests on this rig were monitored and recorded for gear diagnostics research. The primary mode of failure on all five tests was surface pitting, ranging from light and moderate pitting on a single tooth to heavy pitting and spalling over a majority of the gear tooth surface, on a number of teeth.

A graphical sketch of the spiral bevel gear fatigue rig is shown in figure 3. The primary purpose of this rig is to study the effects of gear tooth design, gear materials, and lubrication types on the fatigue strength of aircraft quality spiral bevel gears. The use of this fatigue rig for diagnostic studies is extremely practical, since spiral bevel gears are used extensively in helicopter transmissions to transfer power between nonparallel intersecting shafts. Vibration data from an accelerometer mounted on the pinion shaft bearing housing was captured using a personal computer with an analog to digital conversion board. The 12-tooth test pinion, and 36-tooth gear have a 1 in. face width, and a 90 degree shaft angle. The pinion transmits 720 Hp, at a nominal speed of 14 400 rpm. Figure 4 illustrates the damage on the pinion at three distinct times during a single fatigue test. As seen in figure 4(a), a small pit was first seen when the rig was shut down at 5.5 hr. The damage spread to cover more than 75 percent of the tooth at 12.03 hr, as seen in figure 4(b). At the end of the test, 17.79 hr into the run, the damage covered the majority of three adjacent teeth, with one tooth experiencing a partial tooth fracture, as seen in figure 4(c).

Another spiral bevel gear fatigue rig, similar to the one shown in figure 3, is also used to run face gear fatigue tests. The application of face gears to aircraft transmissions is part of an advanced rotorcraft transmission technology program. Face gears had never been tested at high speeds and high loads. The primary objectives of the face gear fatigue tests were to determine the load capacity and the primary failure mechanism for this type of gear. A standard 28 tooth spur gear drives the 107 tooth face gear at 19 107 rpm with 600 in./lb of torque. Again, vibration data from an accelerometer mounted on the pinion shaft bearing housing was captured using a personal computer. A total of four face gear fatigue tests were monitored and recorded for gear diagnostics research. Tooth fracture and gear tooth surface pitting were the primary failure modes for all four tests. The damage ranged from pitting with partial tooth breakage on one test to severe pitting with complete tooth fracture of several teeth, as illustrated in figure 5.

A graphical sketch of the 500 Hp transmission test facility at NASA Lewis is shown in figure 6. The primary purpose of this rig is to perform basic research on a complete helicopter transmission system. The five tests performed on this rig, listed in table II, were done as a joint NASA/Army/Navy advanced lubricants research program. The main objective of this program was to determine the relative effects of various transmission lubricants on the failure of critical components. An OH-58 helicopter main rotor transmission gearbox was used in this test. Vibration signals from a number of accelerometers along with oil samples were obtained throughout each test. As seen in table II, damage in the tests ranged from micro-pitting on bearings to gear tooth spalls and heavy wear, and housing cover cracks.

GEAR FAULT DETECTION METHODS

A number of previously published and newly developed methods to specifically detect damage on gear teeth were applied to experimental data from the spur gear fatigue rig, spiral bevel gear fatigue rig, and the face gear fatigue rig. The primary purpose was to verify the various methods with naturally occurring faults and to determine their relative performance. Some basic theory behind each method along with an overview of the results obtained using each method are given below.

Method FM0 is formulated to be a robust indicator of major faults in a gear mesh by detecting major changes in the meshing pattern (ref. 11). FM0 is found by dividing the peak-to-peak level of the signal average by the sum of the mesh frequency and its harmonics. In major tooth faults, such as breakage, the peak-to-peak level tends to increase, resulting in FM0 increasing. For heavy distributed wear or damage, the peak-to-peak remains somewhat constant but the meshing frequency levels tend to decrease,

resulting in FM0 increasing. Example results of method FM0 are shown in figure 7. The results shown in figure 7 illustrate the inconsistent nature of method FM0. It reacted to the pitting damage in spur gear test number 2 (fig. 7(a)). However it gave confusing results when applied to the spiral bevel fatigue test (fig. 7(b)) and erratic results when applied to face gear fatigue test number 5 (fig. 7(c)). As seen in figure 7(c), for the face gear tests, FM0 fluctuated radically under nominal conditions and increased only minimally at the end when two teeth broke off the gear. In addition, values for FM0 under nominal conditions were different for each test.

Method FM4 was developed to detect changes in the vibration pattern resulting from damage on a limited number of teeth (ref. 11). A difference signal is first constructed by removing the regular meshing components (shaft frequency and harmonics, primary meshing frequency and harmonics along with their first order sidebands) from the original signal. FM4 is obtained by calculating the fourth normalized statistical moment (normalized kurtosis) of this difference signal. For a gear in good condition, the difference signal would be primarily Gaussian noise, resulting in a FM4 value of 3 (nondimensional). When one or two teeth develop a defect (such as a crack or pitting) a peak or series of peaks appear in the difference signal. FM4 will react by increasing to a value above the nominal value of three. Example results of method FM4 are given in figure 8. As seen in this figure, FM4 responded to the pitting damage in spur gear test number 2 (fig. 8(a)), and the pitting and multiple tooth fracture damage in face gear test number 5 (fig. 8(c)). FM4 gave relatively consistent results by detecting the damage in a majority of the spur gear and face gear fatigue tests. FM4 did not react to light pitting damage on a spur gear test nor to a partial tooth fracture on a face gear test. FM4 also did not give a consistent response to the start and progression of pitting damage in the spiral bevel fatigue test, as seen in figure 8(b). FM4 also reverts back to nominal levels as damage spreads to more than one or two teeth.

Methods M6A and M8A are variations of the sixth (M6) and eighth (M8) normalized statistical moments proposed to detect surface damage using vibration signals (Martin, 1989). M6A and M8A are applied to the same difference signal as defined in the definition of FM4. The basic theory behind M6A and M8A is the same as that for FM4, except M6A and M8A should be more sensitive to peaks in the difference signal. The value for nominal conditions is 15 for M6A, and 105 for M8A. Figures 9 and 10 give example results of methods M6A and M8A, respectively, as applied to spur gear test number 2. As seen in figures 8 and 9, M6A and M8A exhibit response patterns similar to the results of FM4, with no significant advantage over method FM4. These results are typical for methods M6A and M8A.

A phase demodulation method was developed to detect local gear defects such as fatigue cracks, pits and spalls (ref. 10). The basic theory behind this technique is that a gear tooth defect will produce sidebands that modulate the dominant meshing frequency. In this method the signal is bandpassed filtered about a dominant meshing frequency, including as many sidebands as possible. The Hilbert Transform is then used to convert the real band-passed signal into a complex time signal, or analytic signal. Using the real and imaginary parts of the analytic signal, the instantaneous phase (I.P.) can be estimated from the filtered sidebands. Teeth with surface damage, or a fatigue crack, will cause a lead or lag in tooth contact during meshing, resulting in transient changes in the gear rotation, which will be reflected in the I.P. function. Figure 11 gives an example of apply the phase demodulation method to the spiral bevel fatigue test. As seen in this figure, the standard deviation of the I.P. does increase after the initial pit is formed. This method, however, is sensitive to noise in the signal, as illustrated by the random fluctuations in the response plot shown in figure 11.

The frequency demodulation method is calculated by determining the rate of change of the instantaneous phase (refs. 7 and 8). This rate of change, or instantaneous frequency (I.F.), is sensitive to the transient rotational speed changes caused by teeth with surface defects, or root cracks, going through the meshing process. The instantaneous frequency and instantaneous phase are different representations of the same physical phenomenon, however the instantaneous frequency is, by definition, more sensitive. A small change in phase within a very short time would result in a correspondingly large change in the I.F. The I.F. is also calculated from a bandpassed portion of the time signal, using the Hilbert Transform. Figure 12 illustrates the results of applying the frequency demodulation method to the spiral bevel fatigue

test data. The usefulness of this method is limited by its extreme sensitivity, as evident by the large random variations in the I.F. plot shown in figure 12.

NA4* is a method recently developed at NASA Lewis to not only detect the onset of damage, but also to continue to react to the damage as it increases (ref. 13). A residual signal is first constructed by removing regular meshing components from the signal (shaft frequency and harmonics, primary meshing frequency and harmonics). The fourth statistical moment of the residual signal is then divided by the average variance of the residual signal, raised to the second power. The average variance is the mean value of the variance of all previous data records in the run ensemble. In addition, the average variance is "locked" when the instantaneous variance exceeds predetermined statistical limits. With this method, the changes in the residual signal are constantly being compared to a weighted baseline of the specific system under nominal, or "no fault" conditions. NA4* is dimensionless, and as with FM4, gives a value of 3 under nominal conditions. Typical results of method NA4* are shown in figure 13. As seen in this figure, NA4* reacted to and increased with the growing pitting damage found in both spur gear test number 2 (fig. 13(a)) and in the spiral bevel gear fatigue test (fig. 13(b)). NA4* also reacted to the heavy wear in face gear test number 5, and had a dramatic response to the fractured teeth at the end of the test. Overall, NA4* detected damage on a majority of the spur gear tests and on all of the face gear tests. NA4* gave a delayed reaction to moderate pitting damage in one spur gear test. NA4* reacts to a variety of gear damage modes ranging from minor gear damage on a single tooth, to major damage over a number of teeth. NA4* also exhibits the ability to increase with progressing gear damage, as seen in figure 13. NA4* is, however, sensitive to speed and load changes, as illustrated by the speed and load induced spikes experienced during the spiral bevel test, figure 13(b).

NB4* is a method developed at NASA Lewis to give a more robust indication of gear tooth damage (ref. 13). NB4* uses the envelope of the signal bandpassed about the dominant meshing frequency. A complex time signal is created in which the real part is the band-passed signal, and the imaginary part is the Hilbert transform of the signal. The envelope is the magnitude of this complex time signal, and represents an estimate of the amplitude modulation present in the signal due to the sidebands. Amplitude modulation in a signal is most often due to transient variations in the loading. The basic theory behind this method is that a few damaged teeth will cause transient load fluctuations unlike the normal tooth load fluctuations, and thus be observed in the envelope in the signal. Similar to the development of NA4*, NB4* is found by calculating the fourth statistical moment of the envelope, and then dividing it by the average variance of the envelope, raised to the second power. With NB4*, the changes in the envelope are constantly being compared to a weighted baseline of the specific system under nominal, or "no fault" conditions. NB4* is dimensionless with a value of 3 under nominal conditions. Typical results of method NB4* are shown in figure 14. Overall, NB4* gave robust reactions to the detected damage on a majority of the tests. NB4* does, in some instances, fail to maintain a warning level, even as the damage is present and in some cases increasing. This can be observed in NB4*'s decrease to nominal conditions after detecting damage in spur gear run number 2 (fig. 14(a)), and in the spiral bevel gear fatigue test (fig. 14(b)).

ADVANCED PLANETARY DIAGNOSTIC METHOD

A new technique was developed to extract the vibration signature of each planet gear in a planetary system (ref. 5). Due to the epicyclic nature of a planetary system, standard time synchronous averaging techniques applied to "fixed axis gears" cannot be applied to planet gears. Attempting to use standard time averaging techniques would result in a composite vibration signal of all of the planets in the planetary system. With this, it would be difficult to detect a single fault on only one planet gear, as the composite signal is basically the average of the faulted planet gear vibration with the vibration of all other planet gears in the system. An enhancement technique was thus developed to obtain the individual vibration signal for each planet in the system. Gear fault detection techniques could then be applied to

each planet on an individual basis. The new method uses the hunting tooth period averaged vibration signal and planetary design information to obtain individual planet vibration signals. The hunting tooth period average is the synchronously averaged vibration signature for a complete hunting period, with the synchronization based on the rotational speed of the carrier. An enhanced planetary vibration average (EPA) algorithm is then used to re-sample and average the hunting tooth signal average. The EPA algorithm is used to breakdown the hunting tooth period signal, and reconstruct the individual planet signals using planet phasing and other planetary design information. Results of applying the EPA algorithm to a simulated planetary system is illustrated in figure 15. A single tooth fault was implanted on planet number 1 of a four planet planetary model. The EPA algorithm was used to obtain the individual vibration signals for each planet in the system. The resulting vibration signal for planet number 1, seen in figure 15(a), clearly indicates the damaged tooth implanted on planet number 1. The resulting vibration signal of one of the undamaged planet gears, seen in figure 15(b), shows only minor effects from the implanted fault on planet number 1.

GENERAL FAULT DETECTION METHODS

Several general fault detection methods were applied to experimental data from the test rigs at NASA Lewis. These methods are not specific to one element in a transmission, as with the gear fault detection methods. The primary purpose was to verify the various methods with naturally occurring faults. Some basic theory behind each method, along with an overview of the results obtained are given below.

A new pattern classification method was developed as an alternative to single-parameter based diagnosis (ref. 2). The new technique uses an array of post processed parameters to detect and identify a failure. It is similar to an artificial neural net, in that it also uses nonparametric pattern classification in its model, thus allowing it to be independent of the probabalistic structure of the system. Unlike a neural net, however, this new method does not require an extensive amount of training to minimize false alarms and undetected faults. The new method uses a vector of processed measurements that are converted to binary numbers through a flagging operation. The flagging operation is used to detect the existence of a fault. When a fault is detected the vector of binary measurements, or flagged vector, is analyzed through a diagnostic model that produces a resulting fault vector. This fault vector is a ranking of the possible faults according to their probability of occurrence. The diagnostic model utilizes a multi-valued influence matrix, which represents a variety of fault conditions, for comparison with the flagged vector in order to determine fault probabilities. The new method was applied to experimental data from the five tests conducted on the 500 Hp transmission test rig, as listed in table II. A standard neural network was also applied to the same data for comparison. The vibration data was post processed using a commercial system to produce the input data for the pattern classifier and neural network. As seen in table III, eighteen different combinations of the five tests were used for training data sets. As shown in table III, the new pattern classification method outperformed the neural net in a majority of the cases, with fewer undetected faults and false alarms. As shown in table IV, on average the new pattern classification method produces less false alarms, and only half as much undetected faults as a standard neural net.

An oil debris monitoring device was evaluated to determine its effectiveness at detecting general failures (ref. 6). Another means of detecting gear and bearing failures is by monitoring the amount and increase in amount of ferromagnetic debris in the transmission oil. The pitting, spalling and excessive wear of transmission components will result in an increase of ferromagnetic debris in the oil. The oil debris monitoring device (ODMD) tested consists of a sensing coil, trapping magnet and micro-controller. As oil passes through the sensing coil, the trapping magnet is repeatedly energized and de-energized. When energized, ferromagnetic debris is collected along the sensing coil. The sensing coil is the inductive component of a radio frequency oscillator. As debris is collected on the coil, the inductance increases and the oscillator frequency decreases. The ratio of the frequency change to trapping time interval is propor-

tional to the bulk concentration of ferromagnetic debris. The ODMD was installed for the five tests, as listed in table II, conducted on the 500 Hp transmission test rig. The capability of the ODMD to detect transmission component failures was not demonstrated. Two of the five tests produced large amounts of debris, however, two separate ODMD sensors failed, possibly due to prolonged exposure to relatively high oil temperatures. The ODMD results were found to be extremely sensitive to oil temperature and flow rate.

A joint time-frequency analysis approach was applied to experimental data to determine its ability to detect transmission faults (ref. 3). Although the method can be used to detect gear and bearing faults, its first application was to verify its ability to detect gear faults. The method uses the Wigner-Ville Distribution to examine the vibration signal in a joint time-frequency domain. The frequency domain alone can provide the spectral contents of the time signal. However, it cannot distinguish phase changes during a complete rotation. In other words, the Fourier transform alone assumes that the time signals are repeatable for each time data acquisition window without considering the effects of any magnitude and phase changes. The joint time-frequency domain method provides an instantaneous frequency spectrum of the system at a number of points throughout the rotation of the gear. The joint time-frequency domain method displays the interactive relationship between time and frequency and thus is capable of displaying any phase and magnitude changes present. Results of applying the joint time-frequency domain method to the vibration data from the spiral bevel gear fatigue test are shown in figure 16. The plots shown in this figure are time/frequency plots over one rotation of the pinion at several times during the test, corresponding directly with the pinion damage photographs shown in figure 4. As seen in figures 4 and 16, progression of the damage from the initial pit to tooth fracture is reflected in the time-frequency plots. Tooth fracture is indicated in figure 16(c) by the disjointed pattern approximately centered about the meshing frequency (2.9 KHz). The joint time-frequency plots contain abundant information on the existence and extent of tooth damage. A post processing method needs to be developed to extract this information from the joint time-frequency analysis results.

DISCUSSION

Overall results indicate that only a few of the gear fault detection techniques proved reliable enough to be used in a HUM system. After applying the different techniques to a number of different gear types and a variety of gear failure modes, only methods FM4, NA4*, and NB4* responded to gear damage on a relatively consistent basis. The other methods either gave inconsistent performance over the various tests, or were very susceptible to minor amounts of noise in the signal.

Of the more successful methods, (FM4, NA4*, and NB4*), none could successfully detect all the failure modes, with no false alarms. FM4 fails to respond to damage distributed over more than one or two teeth. In some instances, FM4 responds to initial damage, but reverts back to nominal levels when the damage progresses. NA4* failed to give a timely response to moderate pitting damage in one test. NA4* and NB4* also exhibit a sensitivity to speed and load changes, which, in some instances, result in false alarms.

One of the more successful methods, NA4*, also exhibits the ability to respond to damage magnitude. Results from the various tests indicate NA4* to be a robust indicator of tooth damage, which shows an increase in response as the damage increases. As illustrated in figure 13, the level of response of NA4* is a function of the magnitude of damage. As the damage progresses, the value of NA4* also increases. From the tests conducted to date, an NA4* response of 15 or greater indicates heavy damage over nearly the whole face width of one or more gear teeth. With continue refinements, NA4* could also serve as a damage estimation parameter. The successful detection and estimation of damage magnitude is a crucial part of a prognostics-based in-flight fault warning system.

The joint time-frequency domain method exhibits good fault detection capabilities, and possibly damage type and magnitude estimation abilities also. As shown in figure 16, the joint time-frequency

domain method produces a comprehensive representation of the gear tooth damage. A post processing program is needed to reduce the information obtained into a single parameter for simple fault detection. The comprehensive amount of information produced by the joint time-frequency method could also contain information on damage magnitude and failure mode. With further research, the results from the joint time-frequency method could also be used for damage magnitude and failure mode estimation, supplementing the results from other methods, such as NA4*.

Combining the new pattern classification method (multiple valued influence matrix) with the more successful fault detection methods is the next step towards creating a highly reliable fault detection tool. The new pattern classification method exhibited better results than a standard neural net, even when using simple post processed parameters as input. Because no one method can successfully detect all of the possible failure modes and conditions, the successful methods need to be combined into a comprehensive detection scheme. With this, the overall detection reliability will be greater, and the overall false alarms will be less than any one method by itself. Thus, by matrixing the experimentally verified fault detection methods for input to the new pattern classification technique, a highly reliable, integrated fault detection tool can be created.

CONCLUDING REMARKS

This paper presented a summary of the transmission diagnostics research work conducted at NASA Lewis Research Center over the last four years. A variety of transmission fault detection methods were applied to experimentally obtained fatigue data. Based on the results, some overall conclusions can be made.

1. Of the gear fault detection techniques, no one method can successfully detect all possible failure modes.
2. The more successful gear fault detection techniques are FM4, NA4*, and NB4*. The newly developed method NA4* also exhibits damage magnitude estimation abilities.
3. The joint time-frequency domain method results in a comprehensive representation of the detected fault. A post processing method is needed to reduce the information obtained into a single parameter for fault detection.
4. Matrixing the successful fault detection methods as input to the new pattern classification technique is the next logical step to creating a highly reliable, integrated fault detection tool.

ACKNOWLEDGMENTS

The author would like to acknowledge the following persons for their contribution to the work reported herein:

Dr. Fred K. Choy, University of Akron
Akron, Ohio (NASA Grant No. NAG3-1376)

Dr. Kourosh Danai, University of Massachusetts
Amherst, Massachusetts (NASA Grant No. NAG3–1458)

Mr. David R. Levasseur, Technology Integration and Development Group, Inc.
Bedford, Massachusetts (NASA Contract No. NAS3-26141)

REFERENCES

1. Astridge, D.G.: Helicopter Transmissions—Design for Safety and Reliability. Inst. Mech. Eng. Proc., Pt. G-J Aerosp. Eng. vol 203, no. G2, 1989, pp. 123–138.
2. Chin, H.; Danai, K.;Lewicki, D.G.: Pattern Classifier for Health Monitoring of Helicopter Gearboxes. Proceedings of the 47th Meeting of the Mechanical Failures Prevention Group. Office of Naval Research, Arlington, VA., 1993, pp. 221–233.
3. Choy, F.K.; Huang, S.; Zakrajsek, J.J.; Handschuh, R.F.; Townsend, D.P.: Vibration Signature Analysis of a Faulted Gear Transmission System. NASA TM–106623, 1994.
4. Decker, H.J; Handschuh, R.F.; Zakrajsek, J.J.: An Enhancement to the NA4 Gear Vibration Diagnostic Parameter. NASA TM–106553.
5. Levasseur, D.R.; Ventres, C.S.: Advanced Vibration Diagnostic Methods for Planetary Systems. SBIR Phase I Final Report, NASA Contract No. NAS3–26141, 1991.
6. Lewicki. D.G.; Blanchette, D.M.; Biron, G.: Evaluation of an Oil-Debris Monitoring Device for use in Helicopter Transmissions. NASA TM–105830, 1992.
7. Liu, Y.;Chen, K.X.;Zhang, S.: Early Detection of Gearbox Fault Using Frequency Demodulation. Proceedings of the 3rd International Machine Monitoring and Diagnostics Conference, Society for Experimental Mechanics, Bethel, CT, 1991, pp. 72–76.
8. Lyon, R.H.: Using the Hilbert Transform in Machine Diagnostics. Proceedings of the 3rd International Machine Monitoring and Diagnostics Conference, Society for Experimental Mechanics, Bethel, CT, 1991, pp. 204–206.
9. Martin, H.R.: Statistical Moment Analysis As a Means of Surface Damage Detection. Proceedings of the 7th International Modal Analysis Conference, Society for Experimental Mechanics, Schenectady, NY, 1989, pp. 1016–1021.
10. McFadden, P.D.: Detecting Fatigue Cracks in Gears by Amplitude and Phase Demodulation of the Meshing Vibration. J. Vib. Acoust. Stress Reliab. Design, vol. 108, no. 2, April 1986, pp. 165–170.
11. Stewart, R.M.: Some Useful Data Analysis Techniques for Gearbox Diagnostics. Report MHM/R/10/77, Machine Health Monitoring Group, Institute of Sound and Vibration Research, University of Southampton, July 1977.
12. Zakrajsek, J.J.; Townsend, D.P.; Decker, H.D.; An Analysis of Gear Fault Detection Methods as Applied to Pitting Fatigue Failure Data. Proceedings of the 47th Meeting of the Mechanical Failures Prevention Group. Office of Naval Research, Arlington, VA., 1993, pp. 199–208.
13. Zakrajsek, J.J.; Handschuh, R.F.; and Decker, H.J.: Application of Fault Detection Techniques to Spiral Bevel Gear Fatigue Data. Proceedings of the 48th Meeting of the Mechanical Failures Prevention Group. Office of Naval Research, Arlington, VA., 1994, pp. 93–104.

TABLE I.—1990 DIAGNOSTICS SURVEY RESULTS

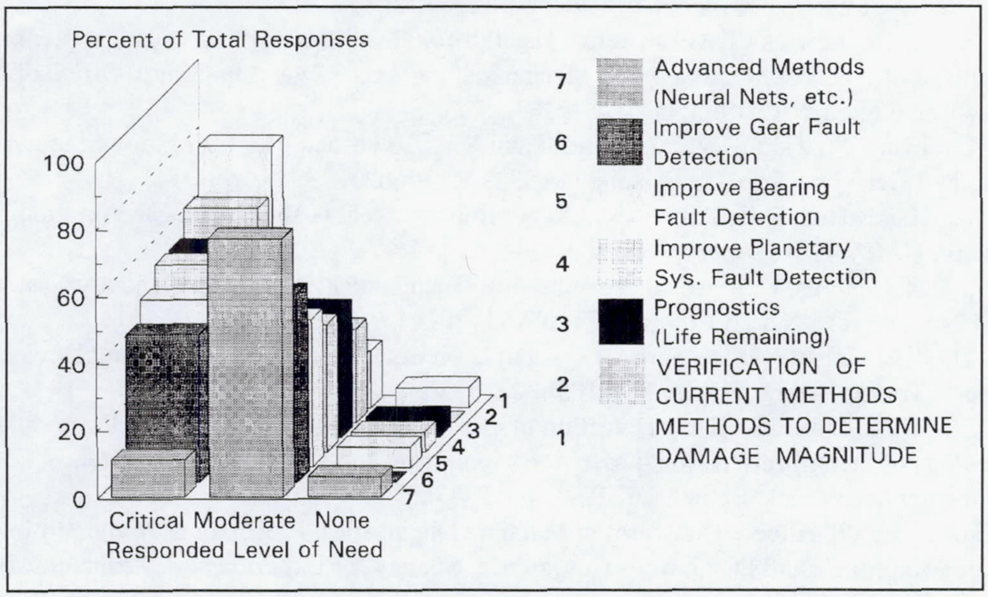

TABLE II.—SUMMARY OF COMPONENT FAILURES FOR THE FIVE TESTS CONDUCTED ON THE 500 Hp TRANSMISSION TEST RIG

Test	Failure
1	Sun gear tooth spall. Spiral bevel pinion scoring/heavy wear.
2	None
3	Planet bearing inner race spall. Top cover housing crack. Planet bearing inner race spall. Micropitting on mast bearing.
4	Planet bearing inner race spall. Sun gear tooth pit.
5	Sun gear teeth spalls. Planet gear tooth spall. Top housing cover crack.

TABLE III.—COMPARISON OF MULTI-VALUED INFLUENCE MATRIX METHOD (MIVIM) TO NEUTRAL NET METHOD FOR DETECTION OF TRANSMISSION FAULTS

Case number	Training data sets	Diagnostic method	Undetected faults	False alarms	Total test errors
1	1	Net	4	0	4
		MVIM	1	3	4
2	5	Net	1	2	3
		MVIM	3	2	5
3	1, 2	Net	4	0	4
		MVIM	2	2	4
4	1, 3	Net	1	2	3
		MVIM	2	0	2
5	2, 5	Net	3	2	5
		MVIM	3	2	5
6	3, 4	Net	2	2	4
		MVIM	0	0	0
7	3, 5	Net	0	3	3
		MVIM	1	0	1
8	4, 5	Net	3	0	3
		MVIM	1	1	2
9	1, 2, 5	Net	1	2	3
		MVIM	1	2	3
10	1, 3, 4	Net	1	0	1
		MVIM	0	0	0
11	2, 3, 4	Net	2	0	2
		MVIM	0	0	0
12	2, 3, 5	Net	1	2	3
		MVIM	1	0	1
13	1, 2, 3, 4	Net	2	0	2
		MVIM	0	0	0
14	1, 2, 3, 5	Net	2	1	3
		MVIM	1	0	1
15	1, 2, 4, 5	Net	1	1	2
		MVIM	1	1	2
16	1, 3, 4, 5	Net	1	0	1
		MVIM	0	0	0
17	2, 3, 4, 5	Net	2	0	2
		MVIM	0	0	0
18	1, 2, 3, 4, 5	Net	1	0	1
		MVIM	0	0	0

TABLE IV.—COMPARISON OF AVERAGE RESULTS OF MULTI—VALUED INFLUENCE MATRIX METHOD (MVIM) TO A NEURAL NETWORK

Diagnostic method	Undetected faults	False alarms	Total average tes errors
Neutral net	1.8	0.9	2.7
MVIM	0.9	0.7	1.6

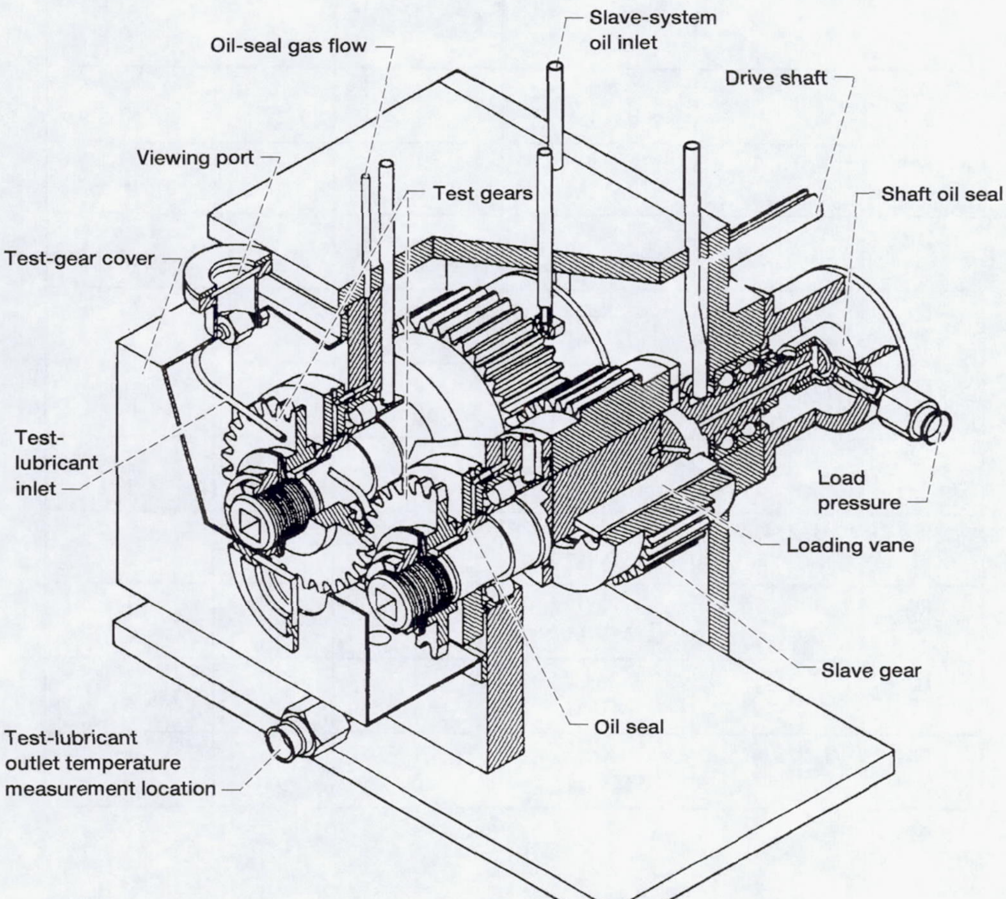

Figure 1.—Spur gear fatigue rig at NASA Lewis Research Center.

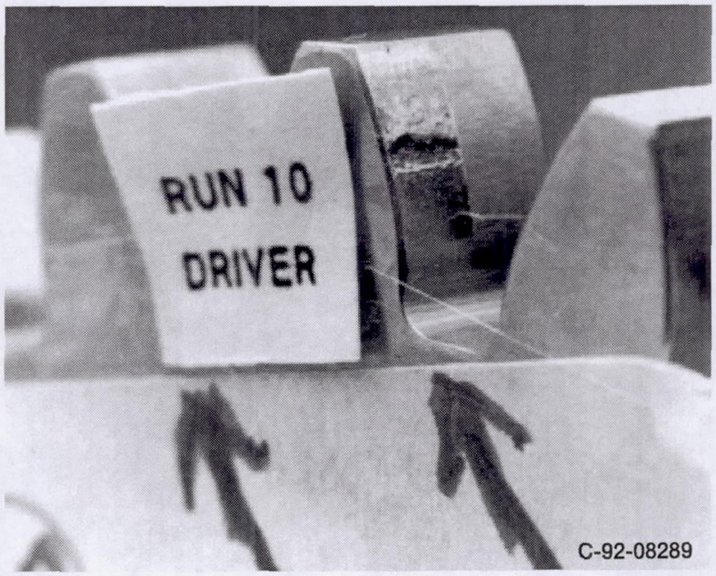

Figure 2.—Sample of pitting damage on spur gear fatigue rig (spur test #2).

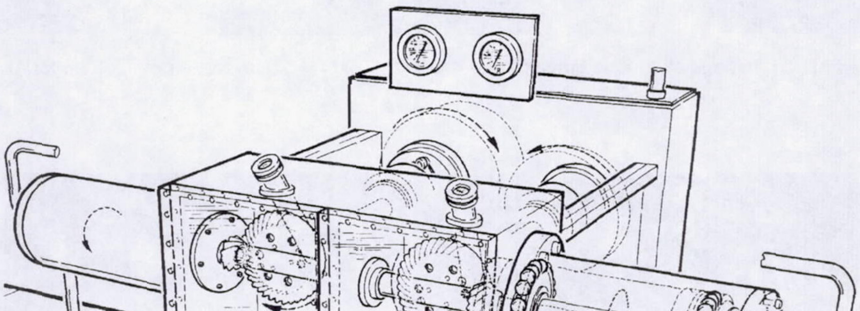

Figure 3.—Spiral bevel gear and face gear fatigue rig at NASA Lewis Research Center.

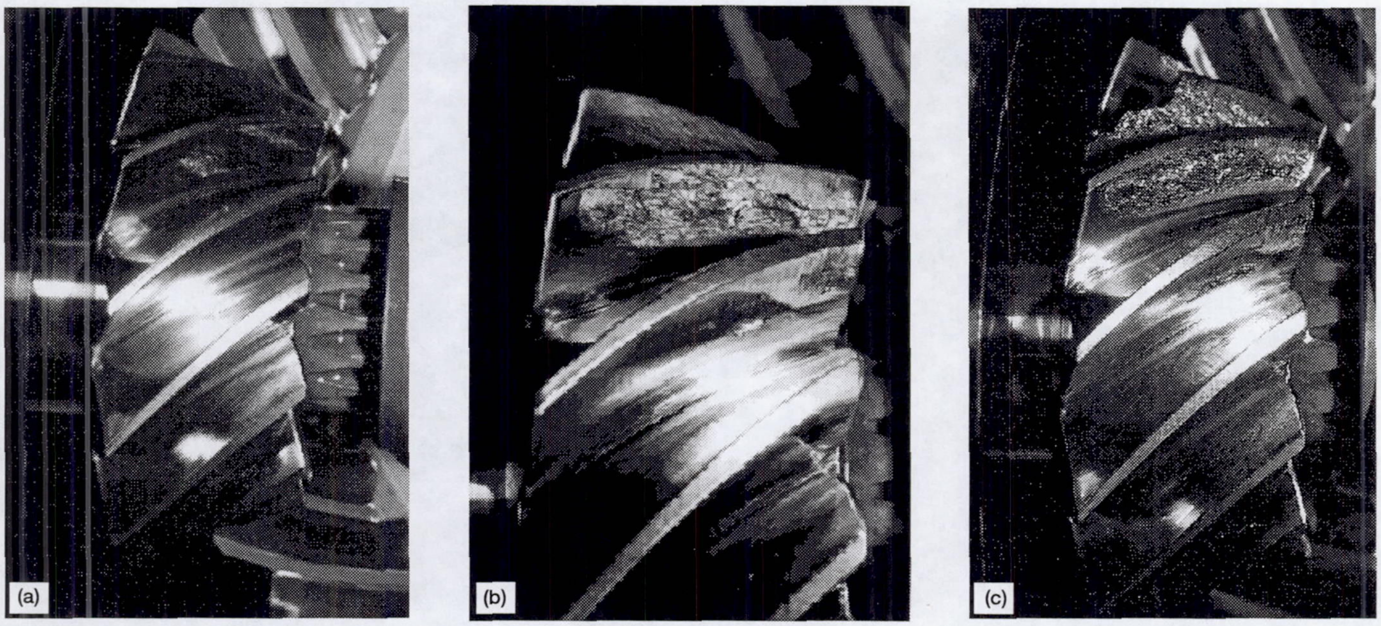

Figure 4.—Spiral bevel pinion damage at various times during the test. (a) At t = 5.5 hr. (b) At t = 12.03 hr. (c) At t = 17.79 hr (end).

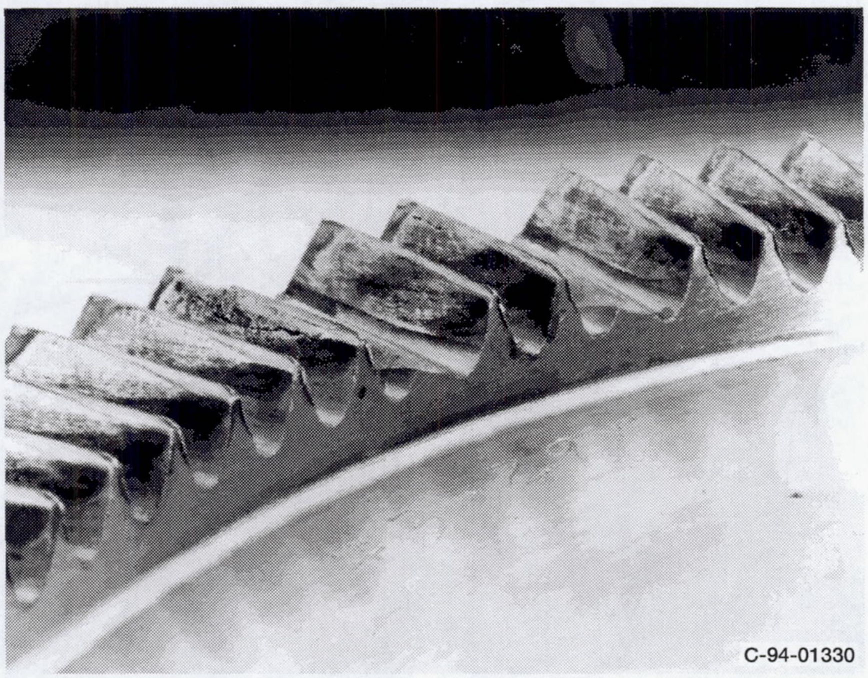

Figure 5.—Sample of pitting and tooth fracture damage on face gear fatigue rig (face test #5).

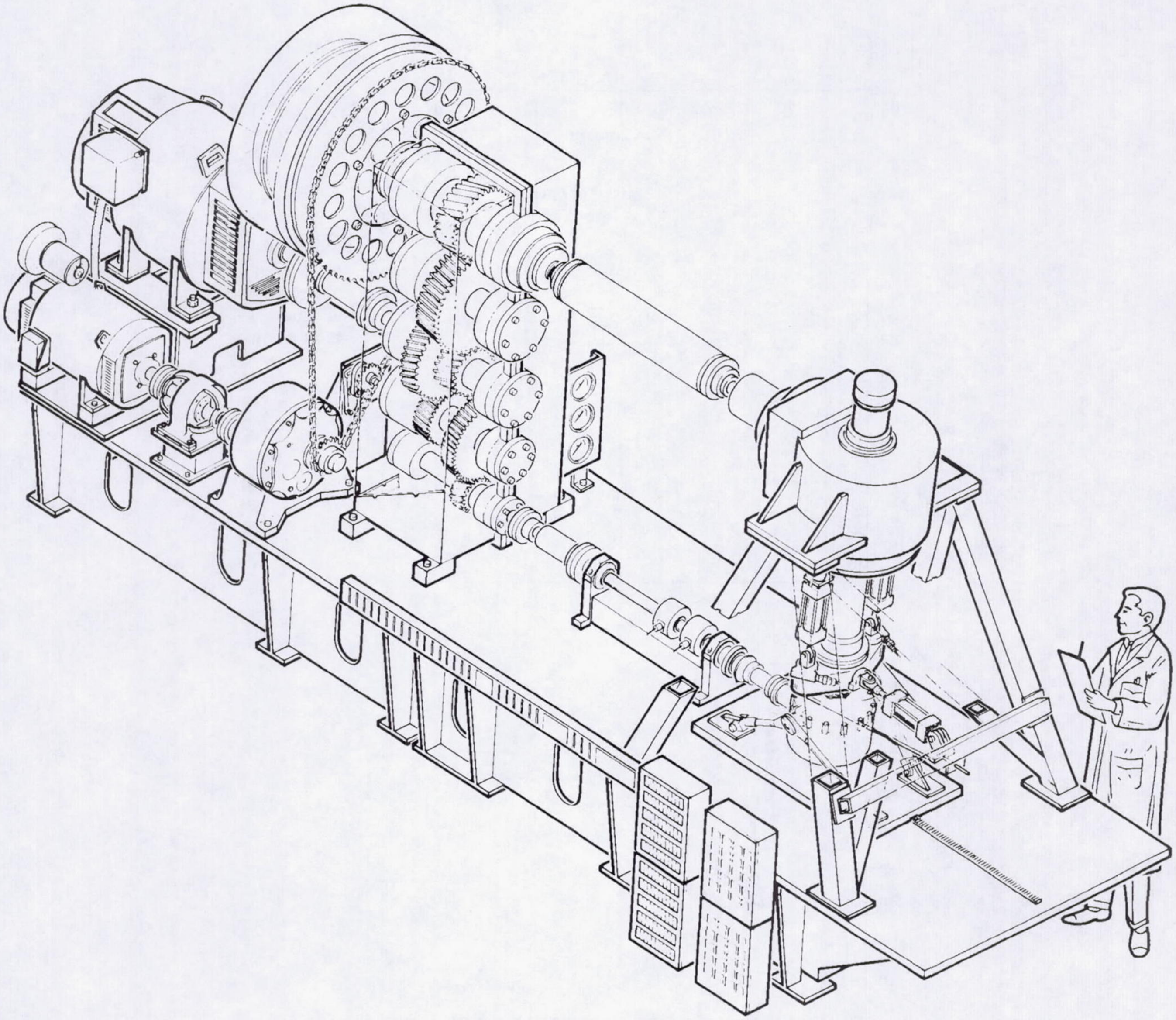

Figure 6.—500 Hp Transmission test facility at NASA Lewis Research Center.

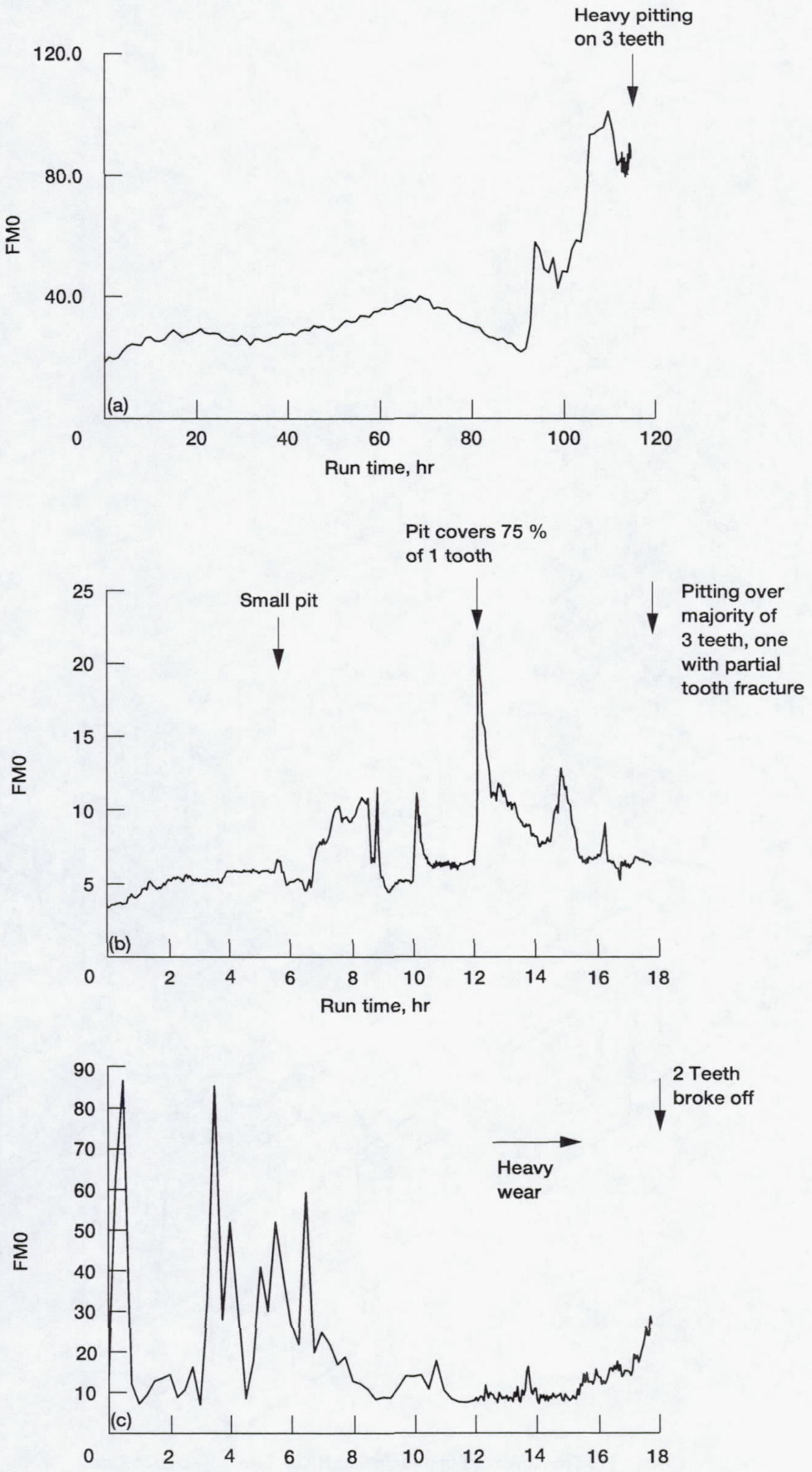

Figure 7.—Example results of method FM0. (a) Spur gear test #2. (b) Spiral bevel gear test. (c) Face gear test #5.

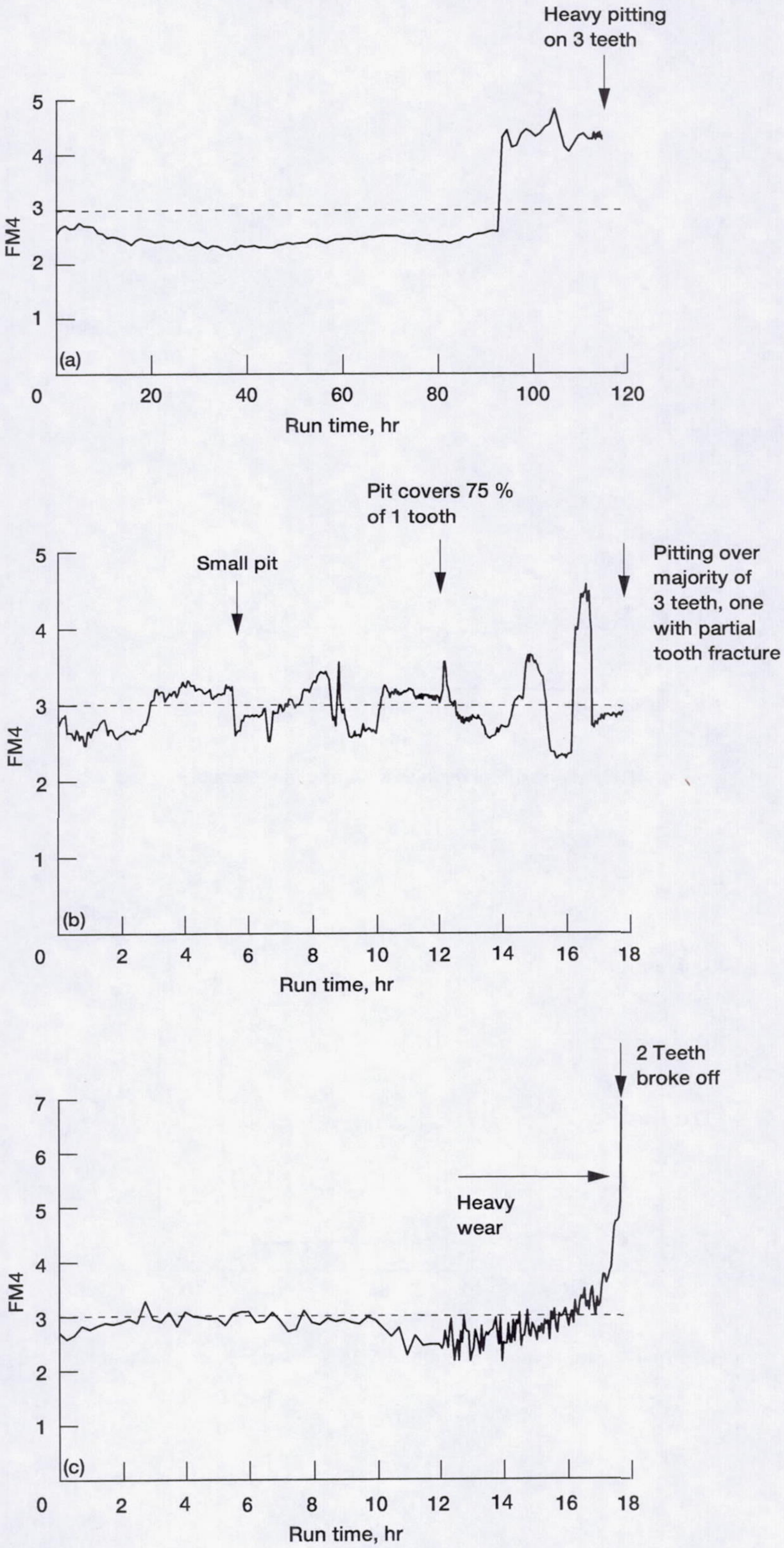

Figure 8.—Example results of method FM4. (a) Spur gear test #2. (b) Spiral bevel gear test. (c) Face gear test #5.

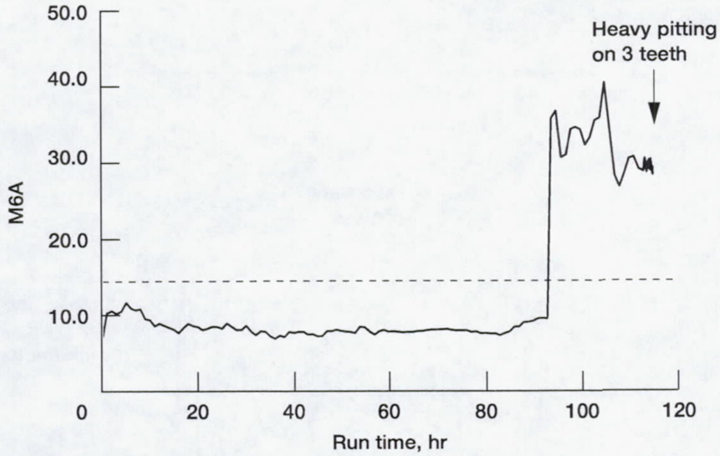

Figure 9.—Example result of method M6A applied to spur gear test #2.

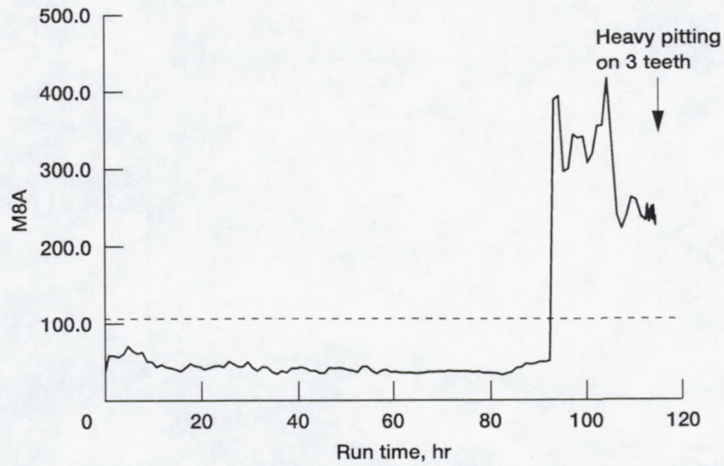

Figure 10.—Example result of method M8A applied to spur gear test #2.

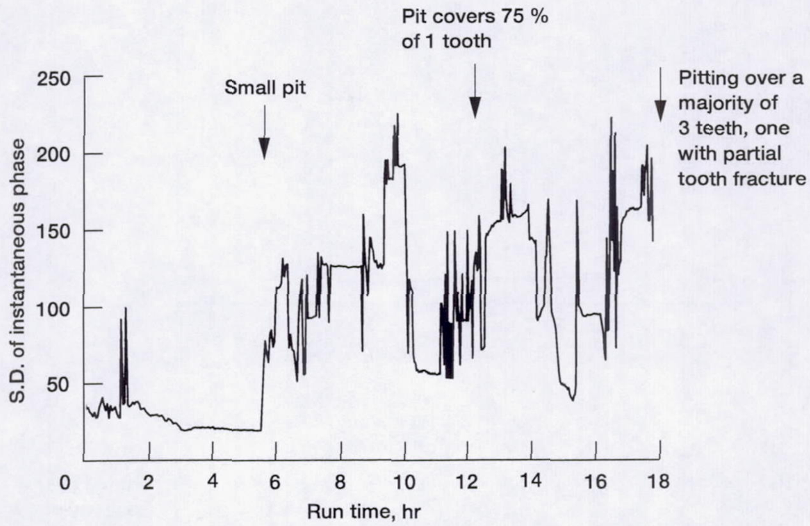

Figure 11.—Example result of phase demodulation method applied to spiral bevel gear test.

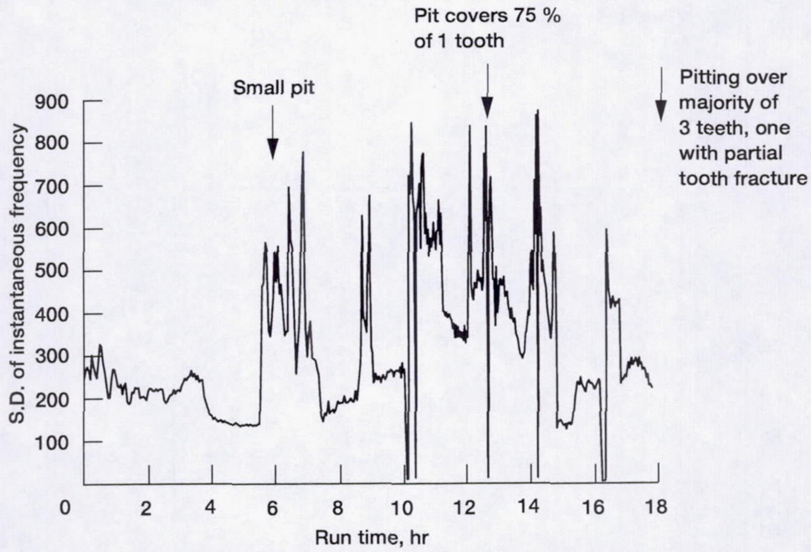

Figure 12.—Example result of frequency demodulation method applied to spiral bevel gear test.

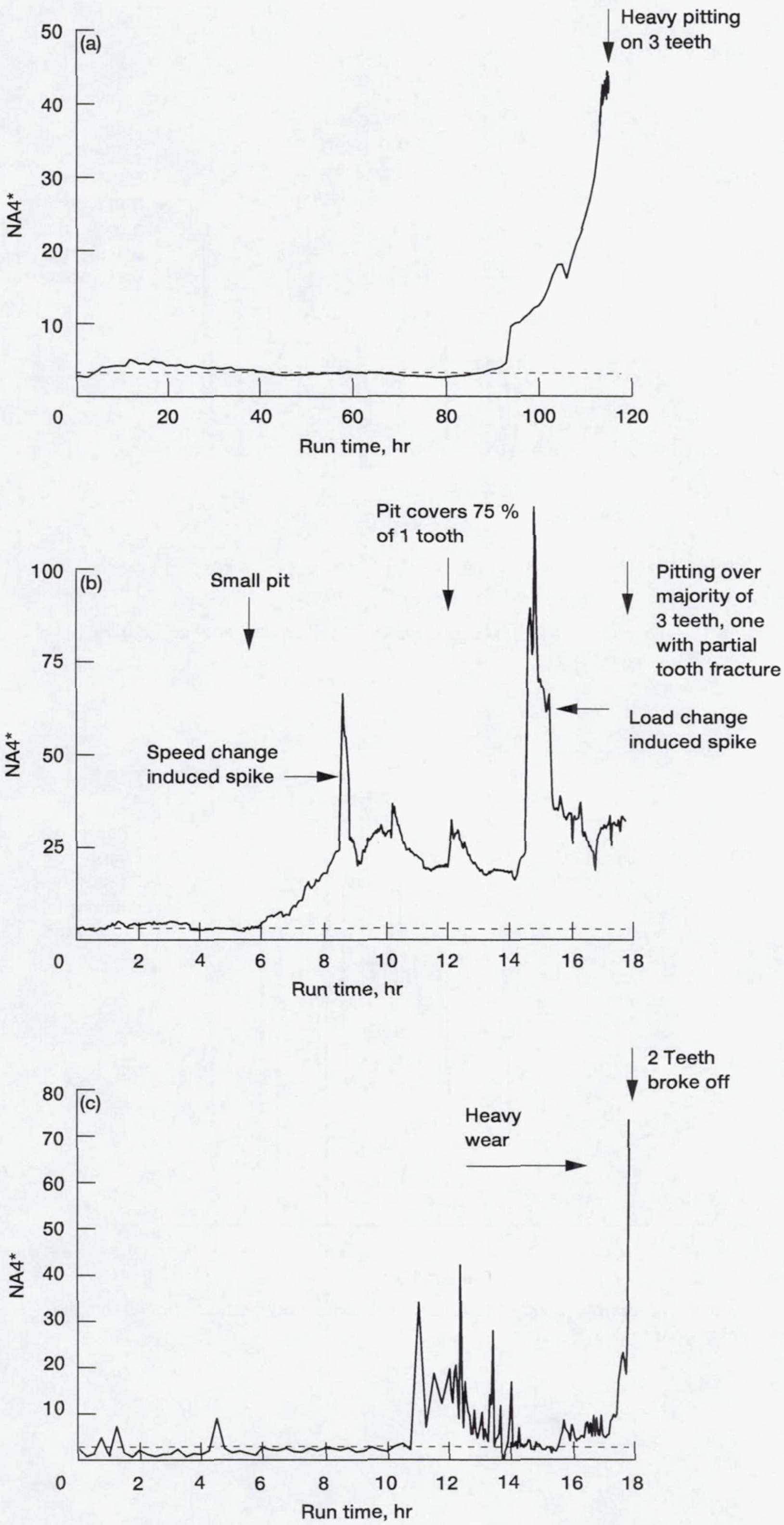

Figure 13.—Example results of method NA4*. (a) Spur gear test #2. (b) Spiral bevel gear test. (c) Face gear test #5.

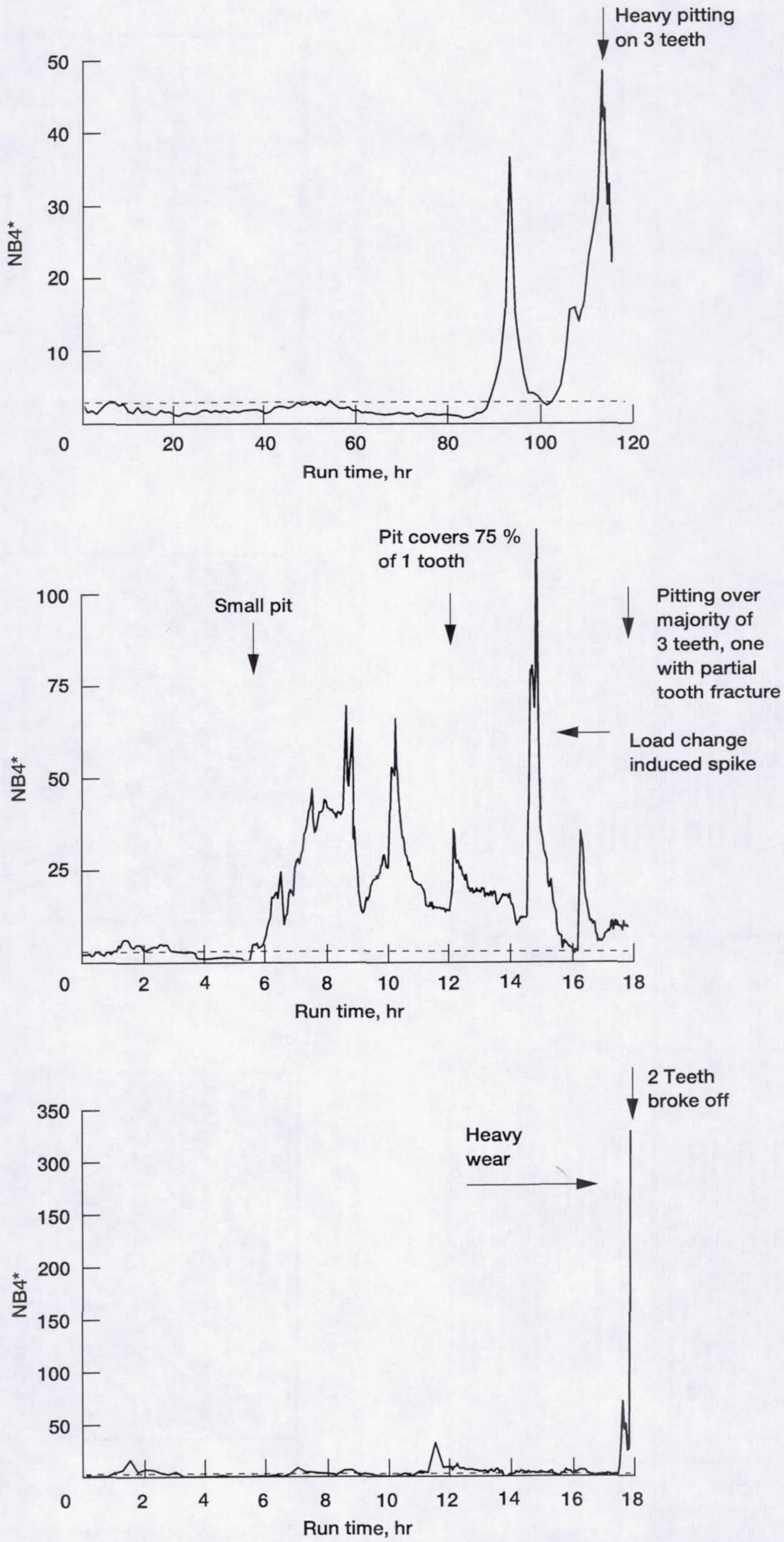

Figure 14.—Example results of method NB4. (a) Spur gear test #2. (b) Spiral bevel gear test. (c) Face gear test #5.*

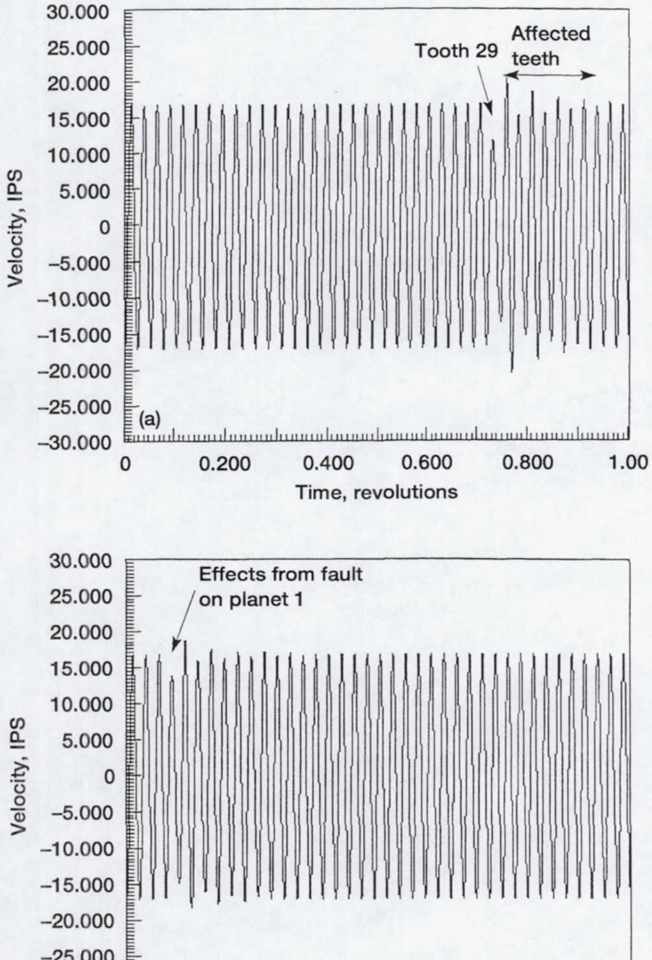

Figure 15.—Theoretical results of advanced planetary diagnostic method (Levasseur, 1991). (a) Enhanced planet average of planet with tooth fault (planet 1). (b) Enhanced planet average of planet with no faults (planet 2).

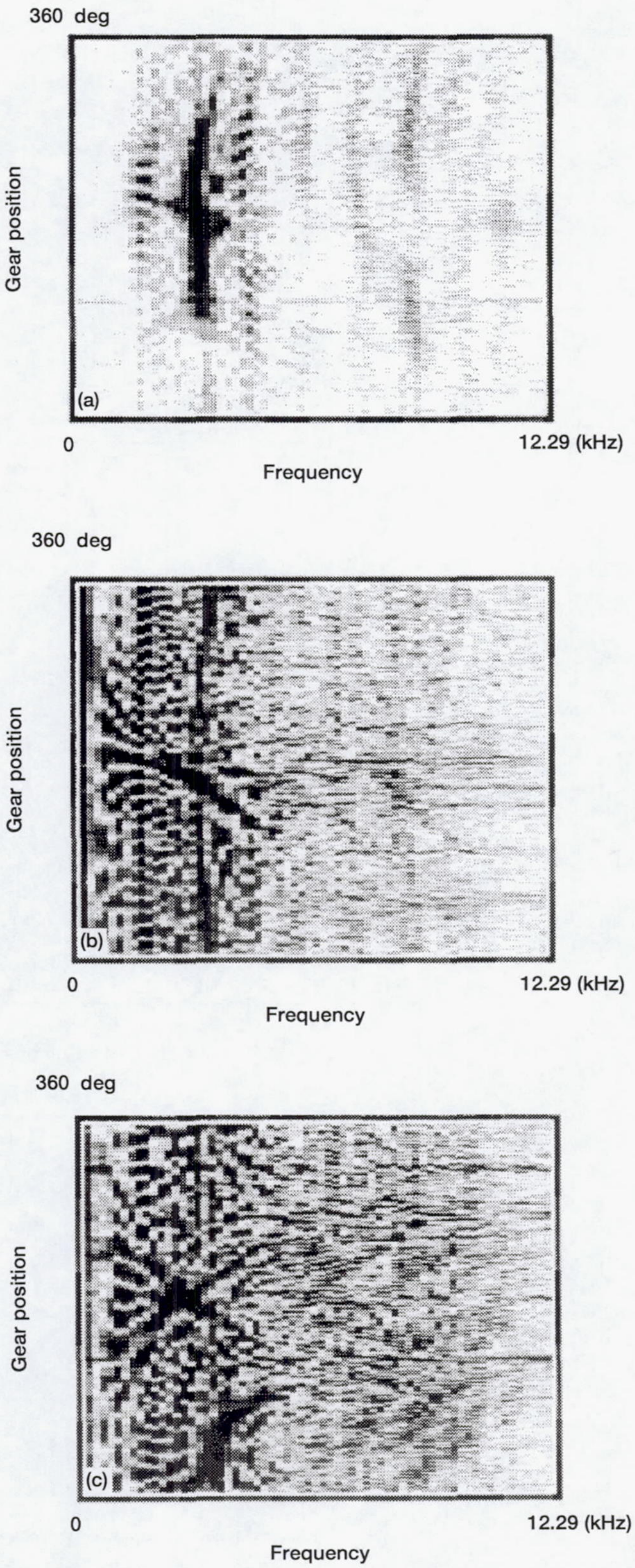

Figure 16.—Results of joint time-frequency domain method applied to spiral bevel gear test. (a) W.V.D. of time averaged signal at t = 5.5 hr. (b) W.V.D. of time averaged signal at t = 12.03 hr. (c) W.V.D. of time averaged signal at end of test (t = 17.79 hr).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1994	Technical Memorandum

4. TITLE AND SUBTITLE

A Review of Transmission Diagnostics Research at NASA Lewis Research Center

5. FUNDING NUMBERS

WU–505–62–36

6. AUTHOR(S)

James J. Zakrajsek

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–9158

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106746

11. SUPPLEMENTARY NOTES

Responsible person, James J. Zakrajsek, organization code 2730, (216) 433–3968.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 37

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper presents a summary of the transmission diagnostics research work conducted at NASA Lewis Research Center over the last four years. In 1990, the Transmission Health and Usage Monitoring Research Team at NASA Lewis conducted a survey to determine the critical needs of the diagnostics community. Survey results indicated that experimental verification of gear and bearing fault detection methods, improved fault detection in planetary systems, and damage magnitude assessment and prognostics research were all critical to a highly reliable health and usage monitoring system. In response to this, a variety of transmission fault detection methods were applied to experimentally obtained fatigue data. Failure modes of the fatigue data include a variety of gear pitting failures, tooth wear, tooth fracture, and bearing spalling failures. Overall results indicate that, of the gear fault detection techniques, no one method can successfully detect all possible failure modes. The more successful methods need to be integrated into a single more reliable detection technique. A recently developed method, NA4*, in addition to being one of the more successful gear fault detection methods, was also found to exhibit damage magnitude estimation capabilities.

14. SUBJECT TERMS

Diagnostics; Fatigue; Transmissions; Gears; Bearings

15. NUMBER OF PAGES

24

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	